

Demonstration of the Structural Performance of Ensa's ENUN 24P in Impact Scenarios in Storage and Transportation

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Abstract

The ENsa UNiversal ENUN 24P is a dual purpose metal cask developed by Ensa for dry storage and transportation of up to 24 PWR non-damaged, high burnup, spent fuel assemblies.

The ENUN 24P cask design meets the principal international storage and transportation regulations for high radioactive material from the IAEA (SSG-15 and SSR-6), as well as those standards required for the licensing in Spain by the Spanish Safety Council (CSN). In addition, it has been also designed to comply with regulations from the US Code of Federal Regulations (10 CFR 71 and 10 CFR 72) and recommendations from the US Nuclear Regulatory Commission. The ENUN 24P cask is currently under licensing process for transportation in Spain and China.

Structural performance of the ENUN 24P cask in the tipover accident scenario of storage, 0.381m drops accident scenario of storage, 1m drop onto a punch accident scenario of transport, as well as penetration impacts in normal condition of storage and transport, have been simulated by state-of-the-art explicit transient finite element methods and evaluated against the design requirements of Section III, Division 1 and Division 3 the ASME Boiler and Pressure Vessel Code.

For the analyses of the accident impact scenarios, the finite element models consisted of the complete package modelled in detail and in three dimensions, to take into account the details in the geometry and the complex interaction between the components.

This paper presents the analysis methodology and modelling technique as well as the brief discussions on the behaviour of the cask in the base down drop as an example.

Introduction

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The ENUN 24P cask design meets the principal international storage and transportation regulations for high radioactive material from the IAEA (SSG-15 and SSR-6), as well as those standards required for the licensing in Spain by the Spanish Safety Council (CSN). In addition, it has been also designed to comply with regulations from the US Code of Federal Regulations (10 CFR 71 and 10 CFR 72) and recommendations from the US Nuclear Regulatory Commission. The ENUN 24P cask is currently under licensing process for transportation in Spain and China.

Ensa has commissioned Arup to perform the analysis and evaluation with the aid of explicit transient finite element (FE) analysis, to demonstrate the structural performance of the cask in the following scenarios:

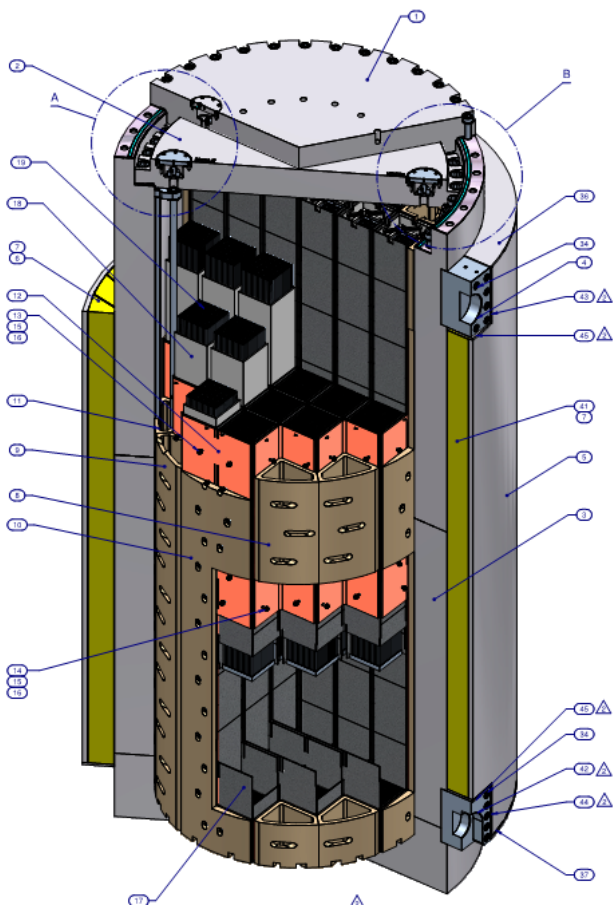
- a) Analysis of the Accident Storage Conditions:
 - Cask tipover onto the reinforced concrete floor of the interim storage facility.
 - Axis vertical drop onto the base from 0.381m height, onto the reinforced concrete floor of the interim storage facility.
 - Centre of gravity over base edge drop from 0.381m height, onto the reinforced concrete floor of the interim storage facility.
- b) Analysis of the Normal and Hypothetical Transport Conditions:
 - Penetration impact of the Normal Conditions of Transport.
 - 1m puncture drop of the Hypothetical Accident Condition of transport.

Description of the Cask

The ENUN 24P cask consists of a monolithic carbon steel body and a double lid bolted closure system. The spent fuel assemblies are accommodated in a basket consisting of an interlock cell structure of stainless steel plates with metal matrix composite tube inserts. A set of “Peripheral plates” are welded around the perimeter of the stainless steel plates for overall structural integrity, and “basket guides” are installed exterior to the stainless steel grid system to make up the circular cross section.

Neutron shielding is provided by solid synthetic resin accommodated between the body and an outer shell. Aluminium fins are installed between the body and the outer shell to facilitate decay heat dissipation. The cask has four bolted trunnions for lifting and handling operations. Two impact limiters will be bolted to the cask during transportation.

The main components of the ENUN 24P are detailed in Figure 1.



Item	Description
1	Outer lid
2	Inner lid
3	Cask body
4	Upper trunnions
5	Outer shell
6	Fins
7	Neutron shielding
8, 9, 10, 11	Basket guides
17	Stainless steel interlock cell structure
18	MMC tubes
19	Fuel assemblies

Figure 1 Main components of the ENUN 24P

Modelling

One FE model was used for the analysis of all the accident drop scenarios of the Storage Condition.

The full model represents the entire cask and consisted of 2.94 million elements. All the analyses were carried out using FE software LS-DYNA version 971.b.

The mesh of the upper part of the FE model of the ENUN 24P is shown below.

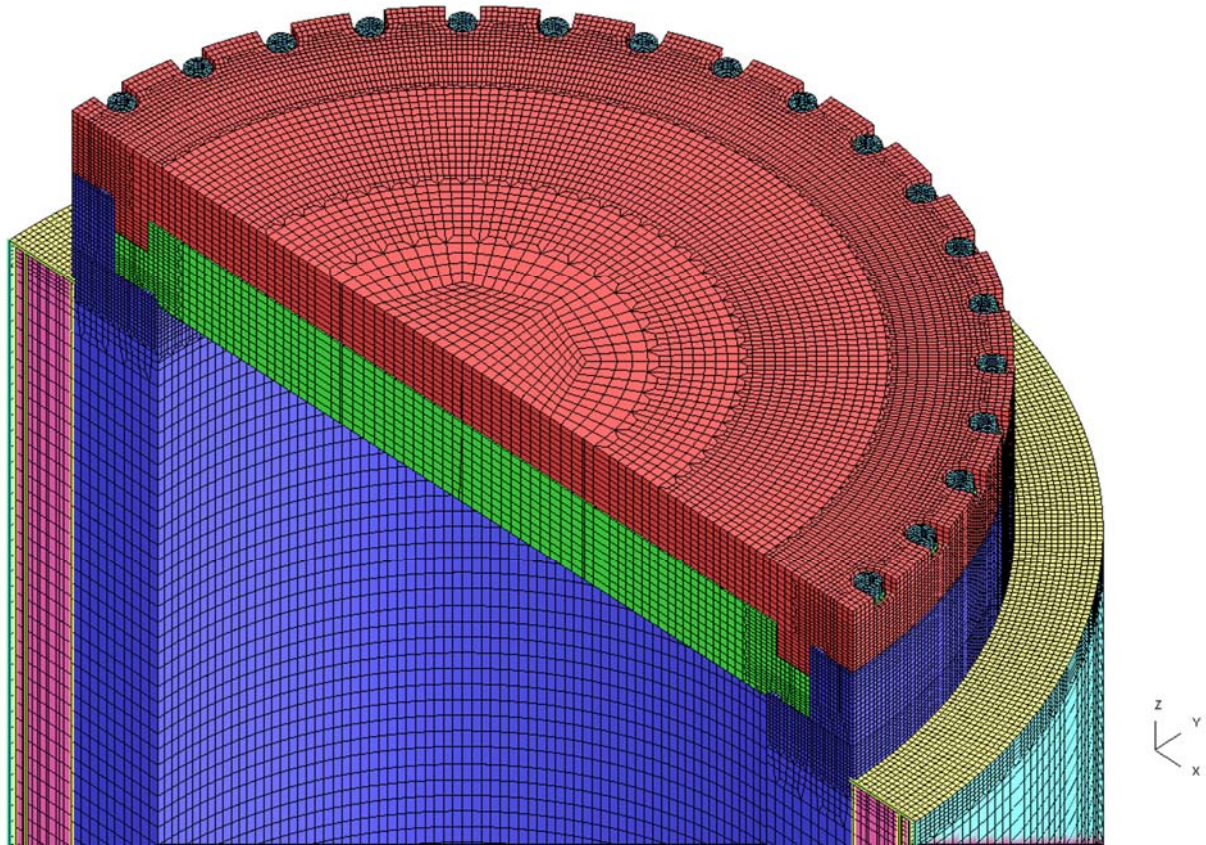


Figure 2 Upper half of the FE model of the ENUN 24P

Modelling principles

The model has been designed following the good practice as defined in TCSC 1087 [1] including the following principles:

- Understand specific capabilities and limitations of the FE software
- Appropriate mesh refinement especially for areas of higher stress gradient, deformation gradient, and smaller geometrical details, and where a higher level of accuracy is required
- Identical mesh for components loaded with similar loadings and repeating geometry at lid-body interface
- Appropriate element quality
- Matching mesh for curved surfaces that are adjacent to each other

Modelling of the bolts

Inner and outer lids are attached to the body by different number of bolts of different sizes. Each bolt was modelled in its entirety using fully integrated selectively reduced eight noded brick elements. Individual threads were not modelled explicitly. Instead, the threaded interface between the bolt and the body bolt holes were modelled with a continuous mesh, with the diameter of the bolt section based on the tensile stress area. Bolt cross sections were modelled as regular polygons with adequate number of elements around the perimeter and in the cross section in accord with best practice.

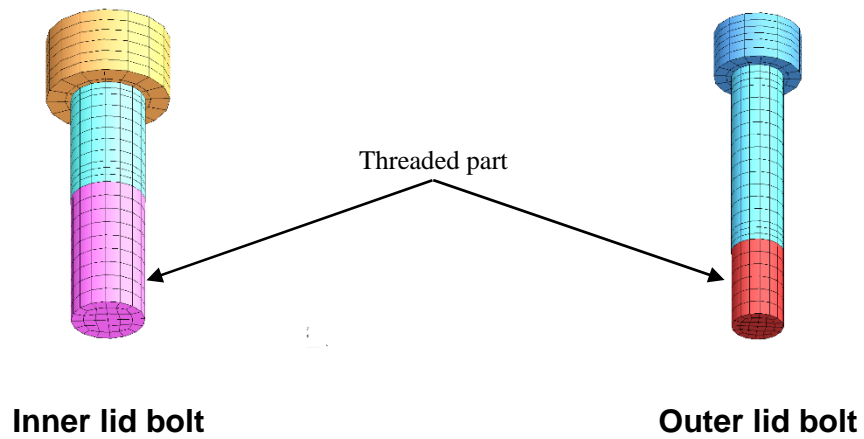


Figure 3 FE model of the lid bolts

Modelling of the cask body

The cask body was also modelled in its entirety using fully integrated selectively reduced eight noded brick elements. The mesh was most refined at the lid-body interface, to be consistent with the mesh of the bolts, to satisfy the requirement of using repeating mesh for repeating units of geometry, to use a mesh that matches with the mesh of the two lids, and to take account of the small geometric details there.

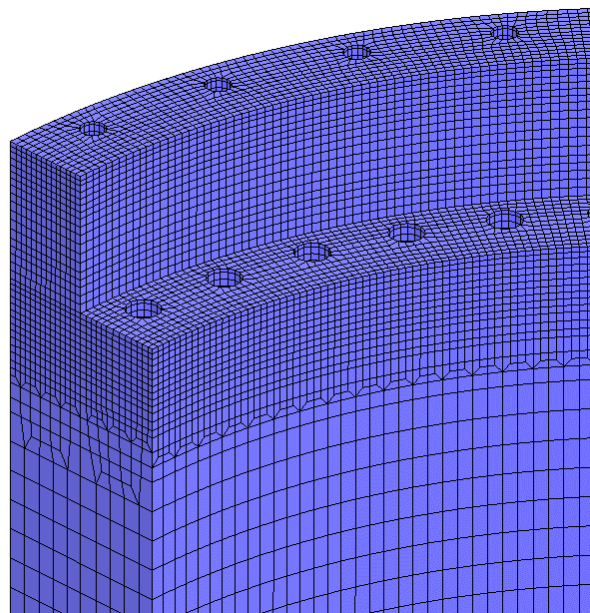


Figure 4 Mesh refinements at the top of the cask body

Modelling of the lids

Similar to the cask body and the bolts, the lids of the ENUN 24P cask were modelled entirely with fully integrated selectively reduced eight noded brick elements. All the bolt holes, bolt head recesses and seal grooves were modelled. The mesh of the two lids were designed to match each other, to match the mesh of the bolts, and to match the mesh of the body.

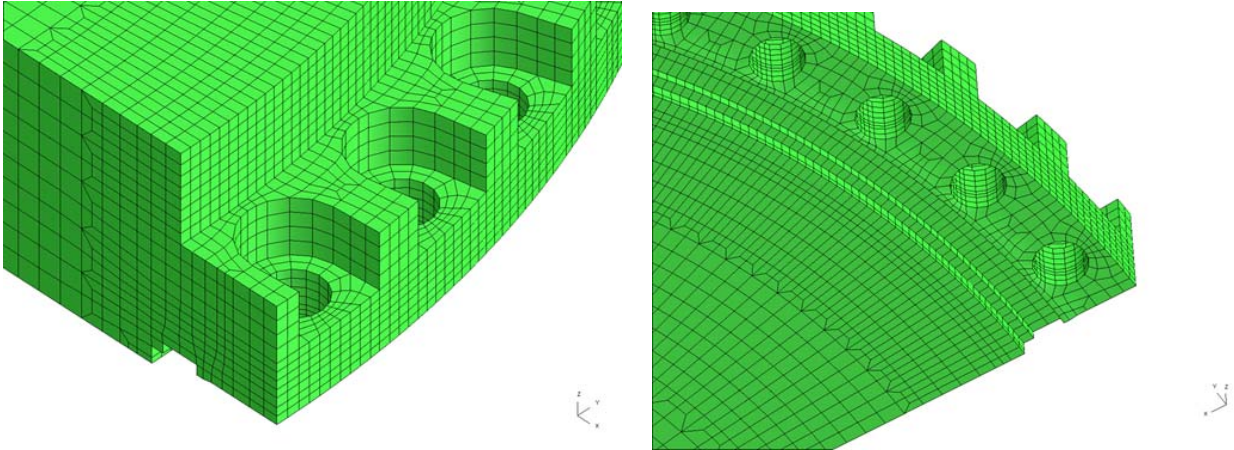


Figure 5 Mesh details of the inner lid

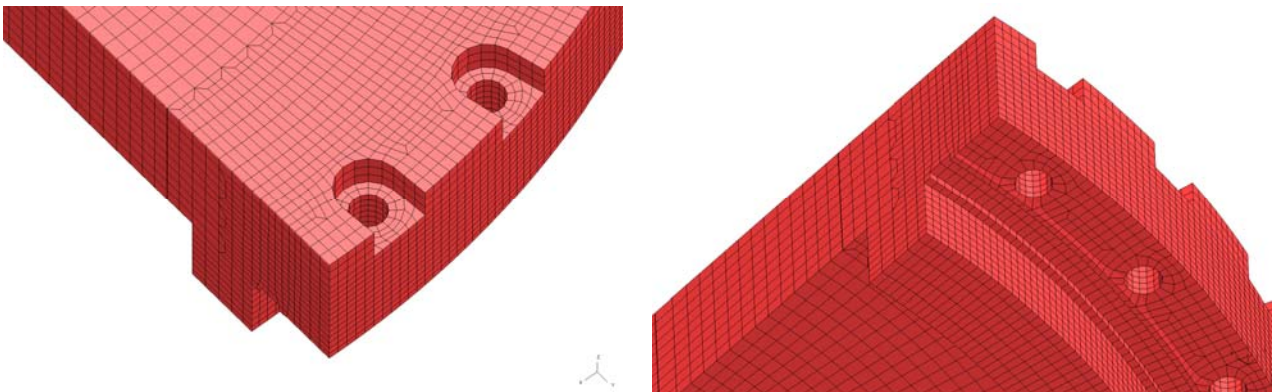


Figure 6 Mesh details of the outer lid

The assembled model of the cask body, the inner and outer lids, bolts and washers are shown on a section through the bolts in Figure 7.

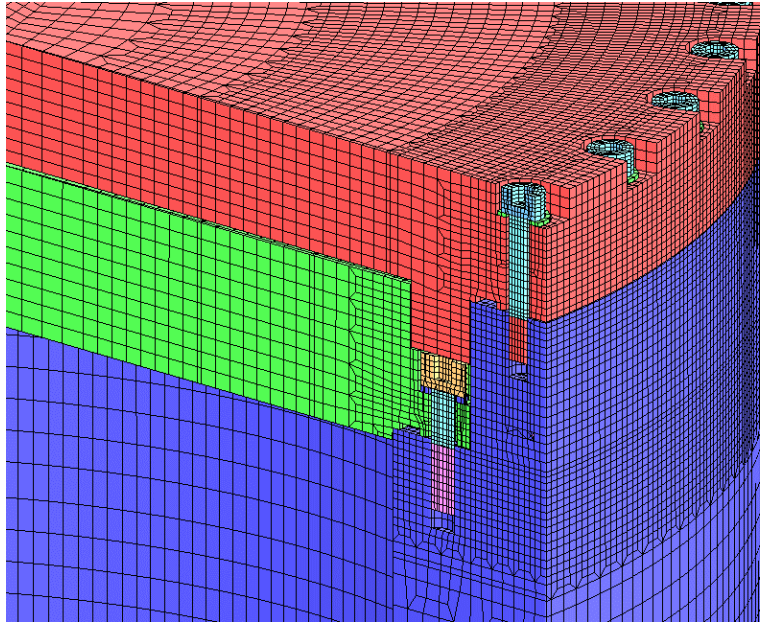


Figure 7 Details of the assembled model around the lid-body interface

Modelling of the basket

Since the basket guides around the perimeter of the steel plate grid system are the only load path between the basket and the cask body, modelling the geometry of the basket guides accurately in order to properly capture the interaction between the basket and the cask body is of primary importance. Solid elements were used as their geometry cannot be accurately represented by thin shell elements. . However, due to their thickness, modelling them with any more than two layers of solid elements is impractical. Since the primary loading on them is compressive, two layers of fully integrated selectively reduced solid elements is adequate to simulate their behaviour in the impact scenarios.

In order to avoid spurious stresses due to mesh mismatch at the curved interface between the basket guides and the cask body in the impact scenarios in which they bear onto each other, the mesh of the basket guides in the hoop direction matches the mesh of the body in one-to-one correspondence

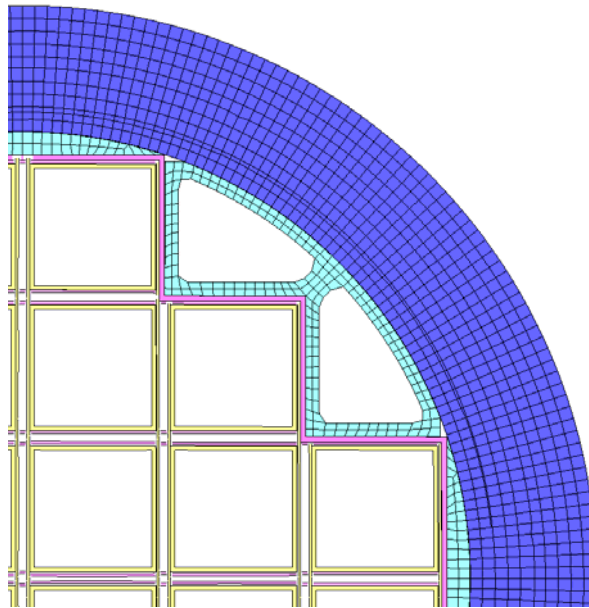


Figure 8 Cross sectional view of the meshes of the basket and the cask body

The stainless steel plates and the MMC tubes were modelled with thin shell elements/

Across each receptacle, the stainless steel plates were modelled with a fine mesh of 12 elements across the span, enough to more than adequately capture the deflection behaviour of the plates. Similarly, the MMC tubes were modelled with a mesh that matches the mesh of the stainless steel plate such that both their deflection and their interface with the stainless steel plates can be adequately simulated. The slots in the stainless steel plates for interlocking plates perpendicular to each other are important construction details of the basket system and they were modelled explicitly.

Modelling of the fuel assemblies

Each fuel assembly was modelled with a “smeared” properties model, with equivalent mass and stress/strain properties to provide a realistic loading onto the basket, but not realistic for detailed prediction of the impact response of the fuel assemblies themselves. The model consisted of solids and thin shell elements, with the assembly of fuel rods, top nozzle and mixing grids modelled with a block of solid elements with smeared properties, and the bottom nozzle with thin shell elements.

Modelling of the impact target

The storage pad at the independent spent fuel storage installation is a reinforced concrete slab with a thickness of 600mm with two layers of steel reinforcement laid on bed rock. Each layer of reinforcement comprises of Ø32mm steel bars at 200mm spacing in two orthogonal directions.

The concrete was modelled with eight noded brick elements and the reinforcing bars were modelled with beam elements. The interaction between the beams and the brick elements was modelled with the *CONSTRAINED_LAGRANGE_IN_SOLID facility in LS-DYNA.

Different target models were used for the different impact scenarios: axis vertical, axis horizontal and centre of gravity over base edge. For each, the mesh was designed such that the solid elements mesh matched the cask profile projected onto target in order to avoid spurious stresses at their interface. FE model of the impact target for the vertical base down drop analysis is shown in Figure 9.

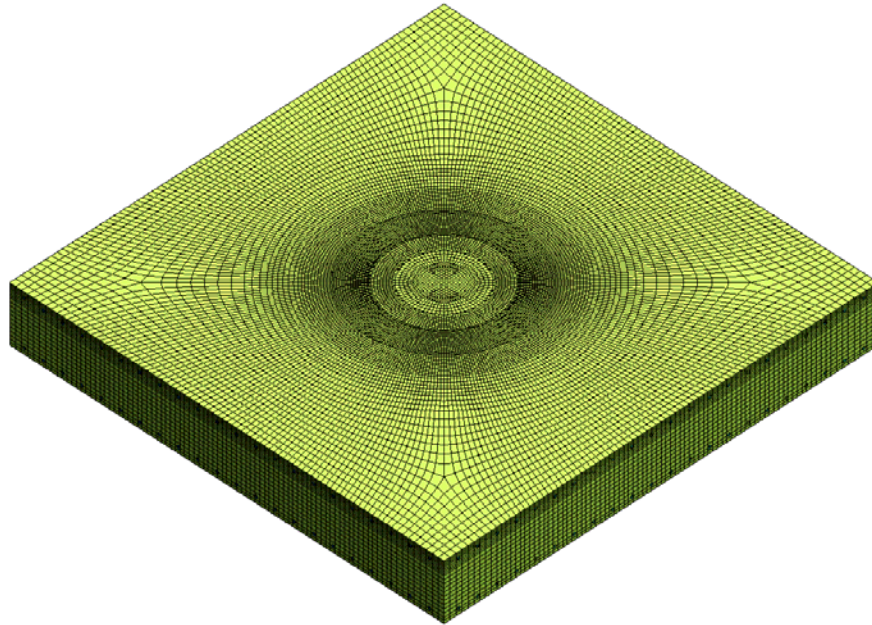


Figure 9 Model of the concrete floor target for the base down drop analysis

Initial conditions

For each analysis, the following initial conditions were applied to the complete cask model:

- Bolt pre-stress.
- Hot condition temperature distribution.
- Maximum internal pressure.
- Initial velocity with respect to the impact target.
- Gravity loading during impact.

They were applied in stages as follows:

1. Bolt pre-stress was applied to the model by dynamic relaxation.
2. Hot condition temperature distribution and internal pressure in the cask cavity were applied by transient analysis.
3. An initial velocity was applied and the transient impact analysis carried out.

Base down drop of the accident scenario of Storage Condition

Among the range of storage and transportation impacts performed, the analysis of the axis vertical base down drop and the behaviour of the cask in this impact is summarised below.

Analysis setup

The cask was oriented with the longitudinal axis perpendicular to the target. The bottom of the cask model was located close to the target at the start of the analysis. The whole model was given an initial velocity of 2.734m/s in a direction perpendicular to the target, representing the initial impact velocity after a drop from 0.381m. At the start of the analysis, the basket and fuel assemblies were resting on the base of the inner cavity of the cask as they would under gravity.

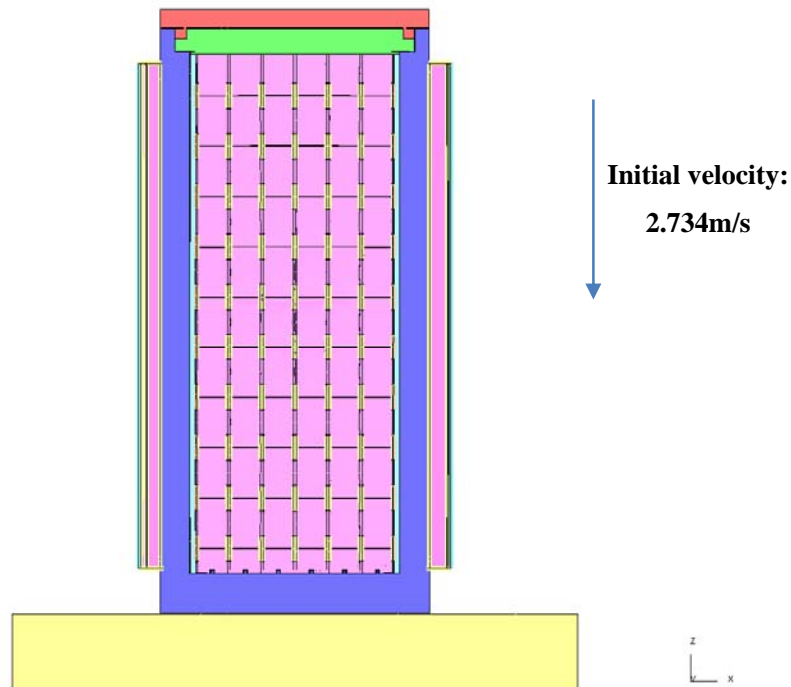


Figure 10 Initial configuration for the base down drop analysis

Discussion of the dynamic response of the cask

As the cask decelerates and then rebounds, the body shortens slightly and the base deflects slightly. This behaviour is illustrated by the displacement time histories in the Z direction (i.e. vertical axis) from three nodes on the body, near the top of the inside of the body on the level of the inner lid seal (N1), near the bottom of the outside of the body just below the base of the neutron shielding (N2), and in the middle on the upper surface of the base (N3) as shown in Figure 11.

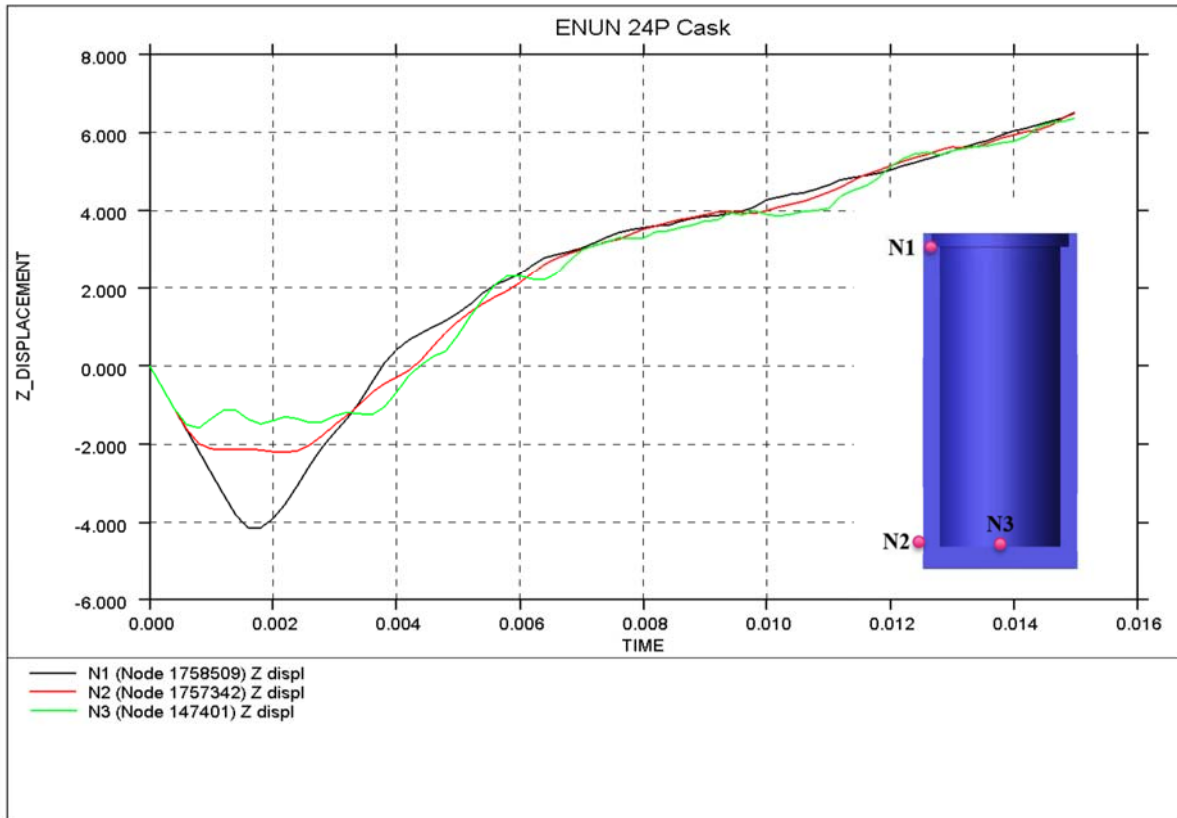


Figure 11 Vertical displacement time histories (in mm vs s) at a various points on the cask body in the base down drop

As the cask decelerates, the lids flexes downwards (i.e. “dished”) as they deflect under their own inertia while supported around the perimeter and flexes upwards (i.e. “domed”) as they rebound but restrained by the bolts.

To illustrate the behaviour of the lid system, the vertical (Z) displacement time history of three nodes - a node on the top surface in the middle of the outer lid (N4), a node on the top surface in the middle of the inner lid (N5), and a node at the top of the body at approximately the level of the inner lid seal face (N1) – have been extracted from the analysis and are shown in Figure 12. The two lids deflect at different rates to different extents, due to difference in bending stiffness, mass and support diameter.

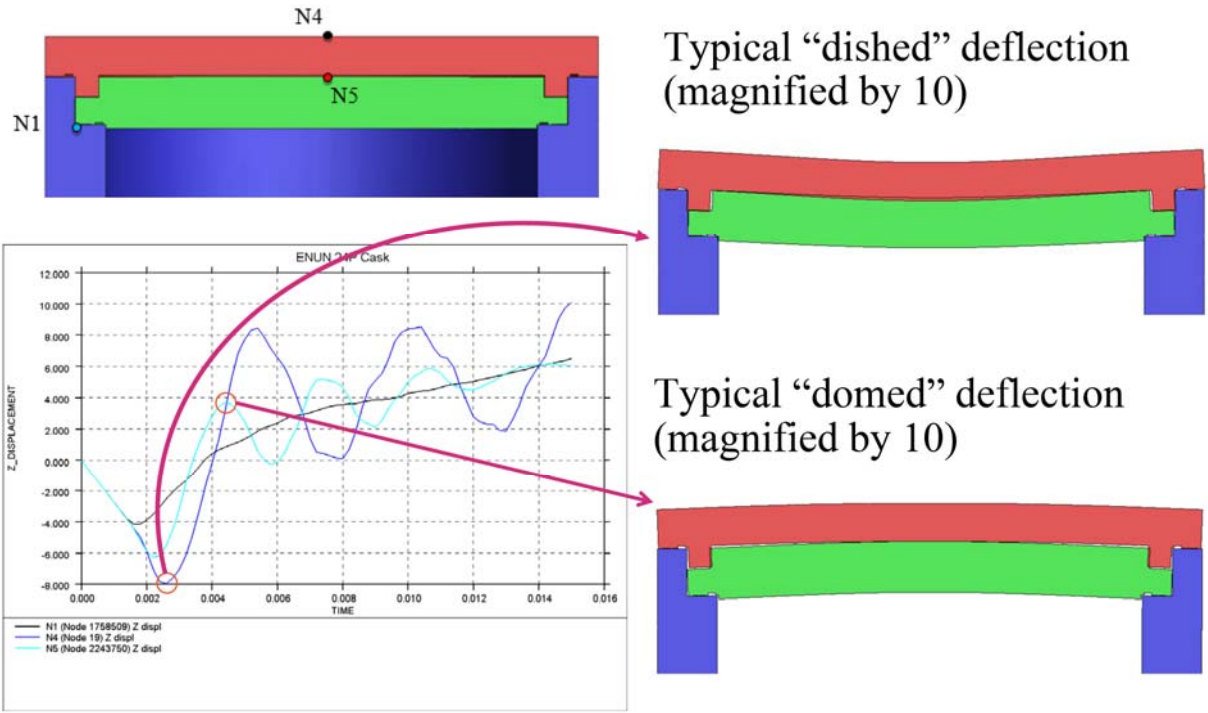


Figure 12 Vertical displacement time histories (in mm vs s) at a various points on the lids and the cask body in the base down drop

The corresponding bending stresses in the lids during the “dished” and “domed” deflections, i.e. in terms of X direct stress on a XZ cross section, at the time of maximum “dished” deflection and at the time of “domed” deflection are shown in Figure 13 and Figure 14.

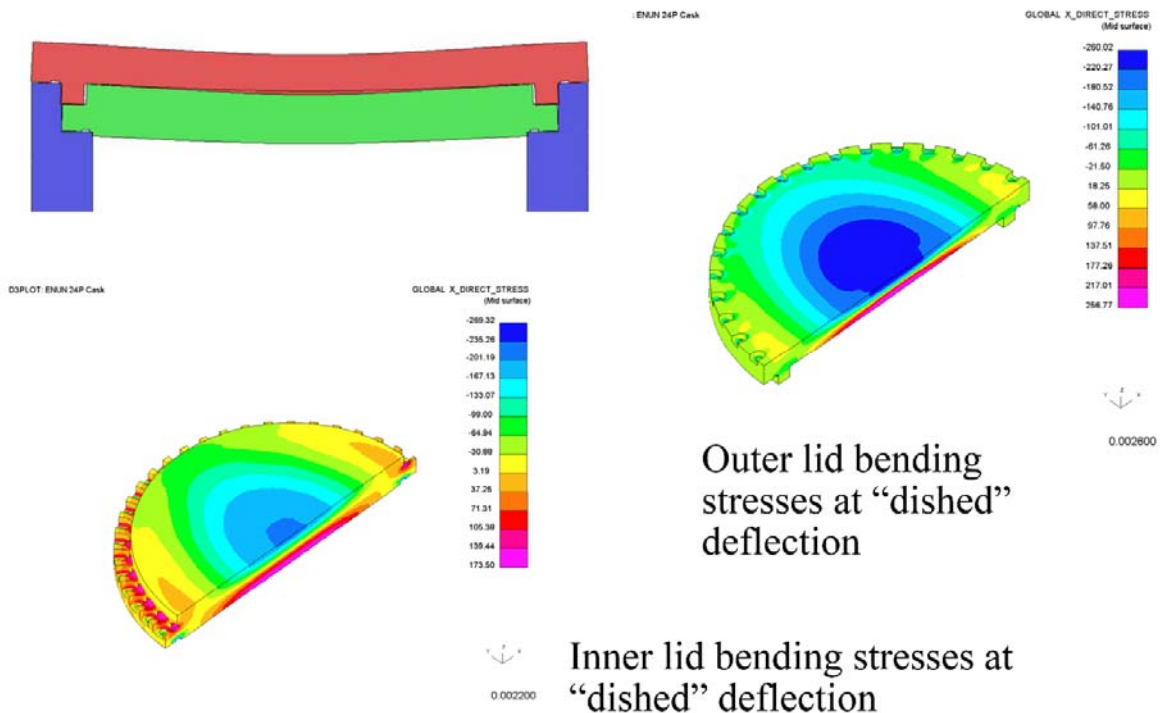


Figure 13 Bending stress distribution in the lids (X direct stress in MPa at a XZ cross section) during a “dishing” deflection in the base down drop

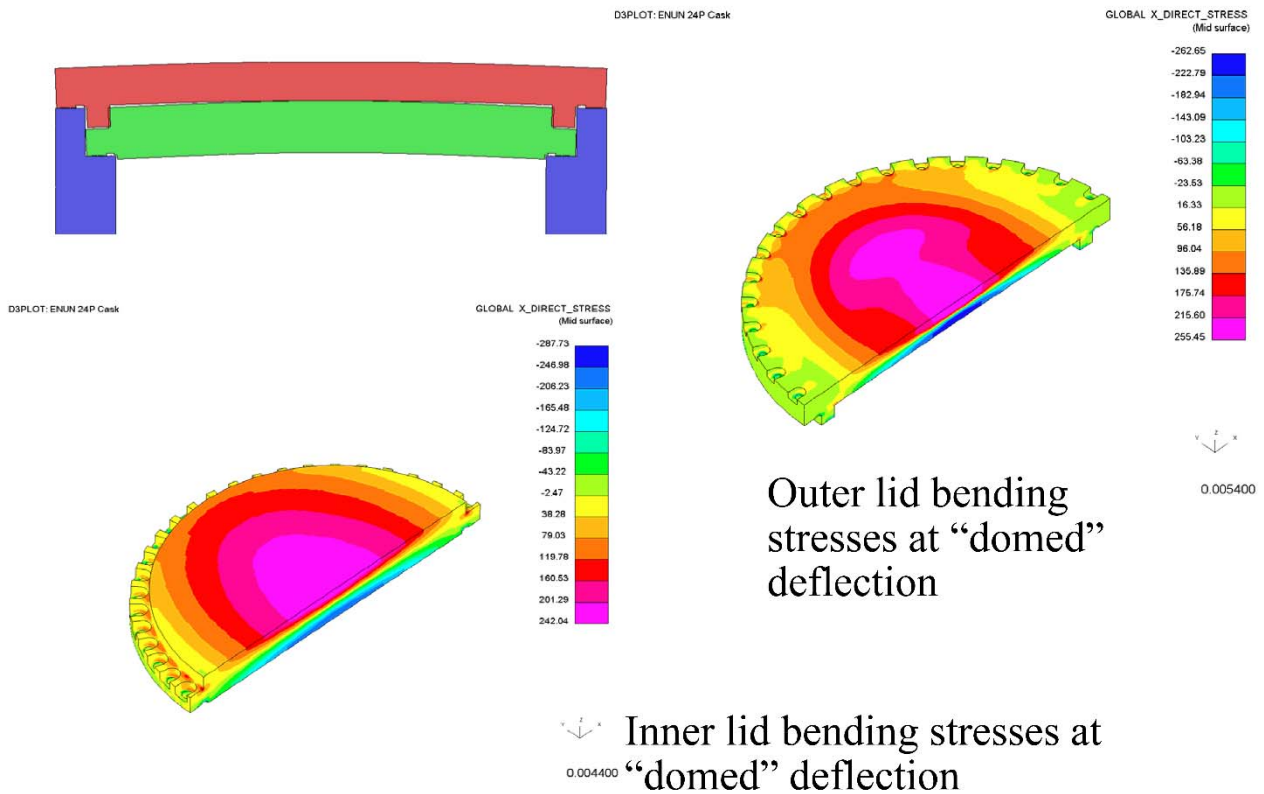


Figure 14 Bending stress distribution in the lids (X direct stress in MPa at a XZ cross section) during a “doming” deflection in the base down drop

When a lid is at a “dished” deflection, it is pivoted about the edge of the seating on the body and the lid bolts were stretched and bent as a result of a “prying” type loading. They are bent towards the centre of the cask.

When a lid rebounds from a “dished” deflection, it jumps from its seating and it is restrained by the lid bolts. The bolts are put into tension and experienced bending but in a different direction to that when the lid was in a “dished” deflection. They are bent away from the centre of the cask. These effects are shown in Figure 15.

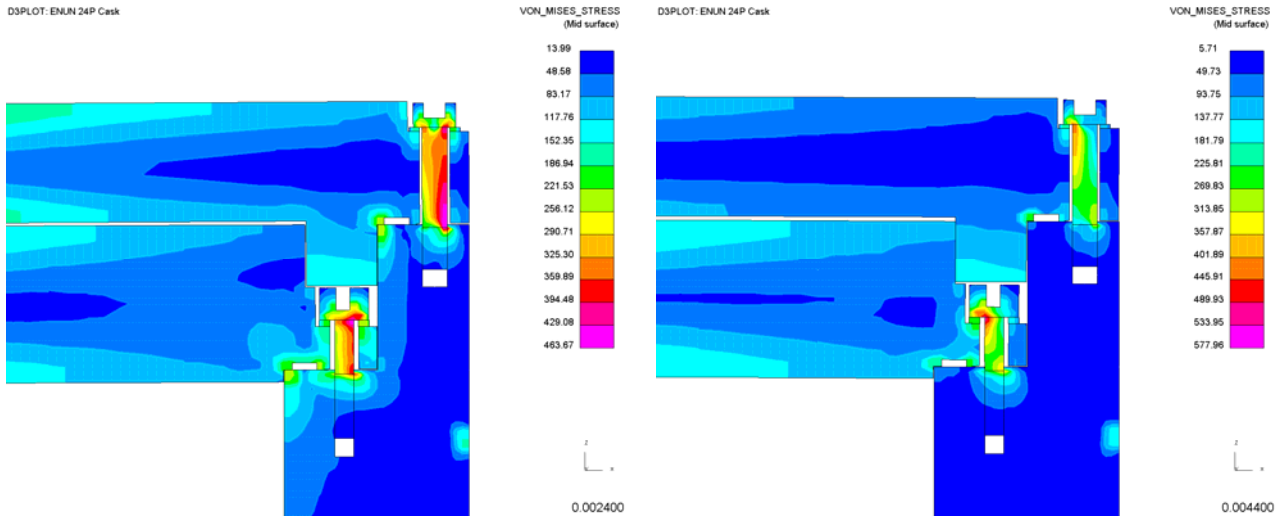


Figure 15 Stress distribution in the bolts (in MPa) corresponding to the “dishing” (left) and “doming” (right) deflections of the lids

Von Mises stresses in the stainless steel plates of the basket at the time of maximum downward displacement of these steel plates is shown in Figure 16. The stresses increase towards the bottom of the basket due to the increase of inertial loading towards the bottom. The effect on the stress distribution from the interlocks and the discontinuities can be seen.

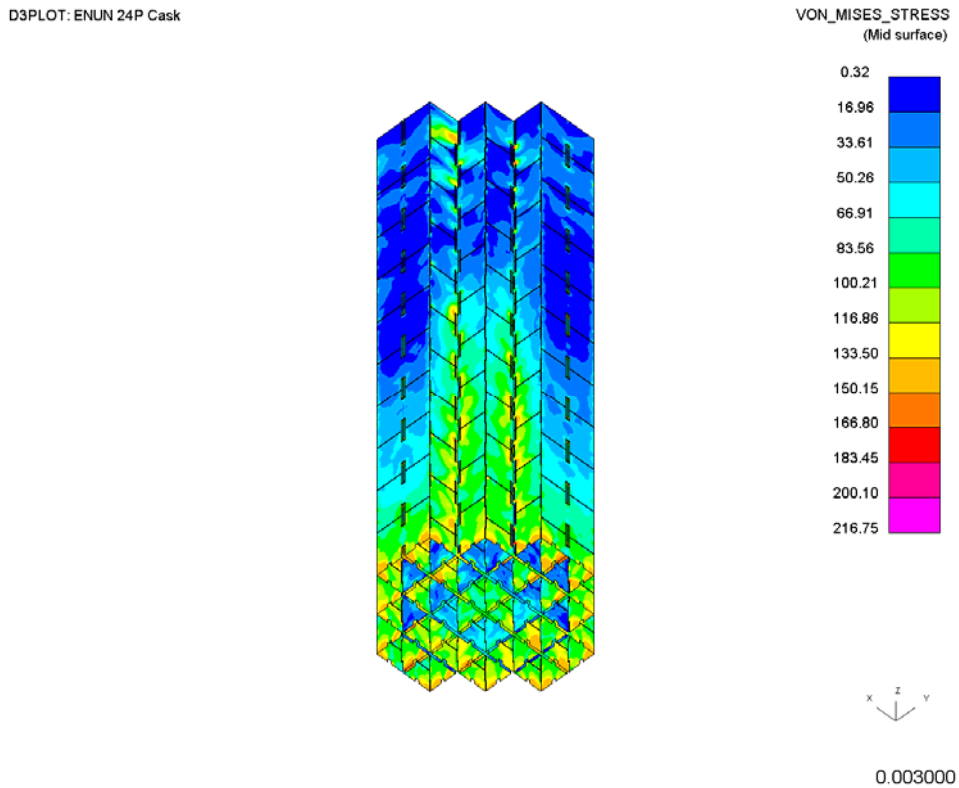


Figure 16 Von Mises stress distribution (in MPa) in the stainless steel plates of the basket at maximum displacement in the base down drop

Conclusions

Ensa has commissioned Arup to perform analysis and evaluation to demonstrate the structural performance of the ENUN 24P dual purpose metal cask under the accident scenarios of the Storage Conditions, penetration impact in the Normal Conditions of Transport, and the puncture drop of the Hypothetical Accident Condition of Transport.

Arup has carried out detailed analyses and evaluation of the ENUN 24P. Modelling for the analysis of the accident scenarios of the Storage Conditions and the behaviour in the base down drop has been described in brief in this paper.

The work has demonstrated that the cask satisfies all the performance criteria of these scenarios.

References

- [1] Transport Container Standardisation Committee, Transport of Radioactive Material Code of Practice - Good Practice Guide - The Application of Finite Element Analysis to Demonstrate Impact Performance of Transport Package Designs, TCSC 1087